

Measurements of the Heavy-Ion Elemental and Isotopic Composition in Large Solar Particle Events from ACE

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Abstract. Using the Solar Isotope Spectrometer (SIS) on the Advanced Composition Explorer (ACE), we have measured the isotopic composition of as many as eleven elements from He through Ni at energies of tens of MeV/nucleon in eleven solar energetic particle (SEP) events that have occurred since November 1997. We find that isotopic composition varies dramatically from event to event. For example, the $^{22}\text{Ne}/^{20}\text{Ne}$ ratio ranges from ~ 0.7 to > 2 times the solar wind value, being lowest for iron-poor events and highest for iron-rich events. We present the SIS SEP isotope measurements to date and show that the strong correlation of elemental and isotopic abundance ratios suggests that elemental and isotopic fractionation are governed by the same process.

1. Introduction

Elemental abundances of solar energetic particles (SEPs) have been measured for many years (e.g., Teegarden, von Rosenvinge, & McDonald 1973) in order to probe the composition of the solar atmosphere and to study particle acceleration and transport processes which may affect the arriving composition. Two distinct categories of SEP events, impulsive and gradual, are generally recognized (Reames 1995a). Elemental abundances in gradual SEP events are known to be highly variable from event to event and are found to be correlated with the ionic charge to mass ratio, Q/M (Breneman & Stone 1985). When corrected for this fractionation (Breneman & Stone 1985; Garrard & Stone 1993) or averaged over many events (Reames 1995b), SEP abundances can be used to determine the elemental composition of the corona more accurately than is possible with spectroscopic measurements for some elements such as noble gases. In principle, the coronal isotopic composition can also be obtained from SEPs (Mewaldt & Stone 1989; Williams et al. 1998), which has not been possible spectroscopically for more than a few isotopes.

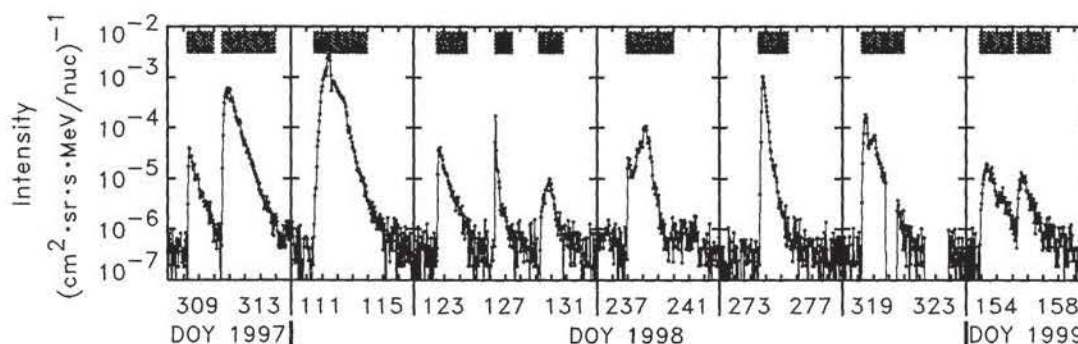


Figure 1. Hourly-averaged fluxes of oxygen nuclei with 21–64 MeV/nucleon measured by SIS, illustrating the time profiles of the 11 SEP events and the time intervals (*shaded boxes*) used in this analysis.

Prior to the launch of the Advanced Composition Explorer (ACE), SEP heavy isotope measurements were relatively few and were available only for elements up to Si (see, e.g., Williams et al. 1998 and references therein). The measured values sometimes involved sums over several SEP events to obtain adequate statistical accuracy and generally agreed with terrestrial abundances within the large uncertainties. Isolated differences were found for some gradual events (Mewaldt & Stone 1989; Williams et al. 1998), and significant enrichments of ^{22}Ne were found in ^3He -rich periods (Mason, Mazur, & Hamilton 1994).

In recent studies using ACE data, large enhancements (up to a factor of ~ 2 over the standard solar values [Anders & Grevesse 1989]) were reported in the 6 November 1997 SEP event for many heavy isotopes from ^{13}C to ^{60}Ni (Leske et al. 1999a). The $^{22}\text{Ne}/^{20}\text{Ne}$ ratio in nine SEP events observed at energies of 24–72 MeV/nucleon by the Solar Isotope Spectrometer (SIS) on ACE was found to vary by more than a factor of 3 from event to event (Leske et al. 1999b), and similar variability was found in other events at lower energies (Dwyer et al. 1999). In this report, we use SIS data to examine the isotopic composition of up to eleven elements in eleven large SEP events and show that although the isotopic abundance ratios vary widely from event to event, the degree of mass fractionation is well correlated with the elemental fractionation. An earlier summary of this work appeared in Leske et al. (1999c).

2. Observations

In the SIS instrument, the nuclear charge, Z , mass, M , and total kinetic energy, E , can be determined for particles with energies of ~ 10 to ~ 100 MeV/nucleon using the dE/dx versus residual energy technique in a pair of silicon solid-state detector telescopes (Stone et al. 1998). For this study, we selected SEP events with sufficient fluxes of high energy heavy ions ($E \gtrsim 20$ MeV/nucleon, where mass resolution is best) to obtain statistically meaningful isotope abundances. Time profiles of the eleven selected events are shown in Figure 1. The peak intensities of these events vary by more than two orders of magnitude at these energies, and their durations also vary. Both coronal mass ejections (CMEs) and

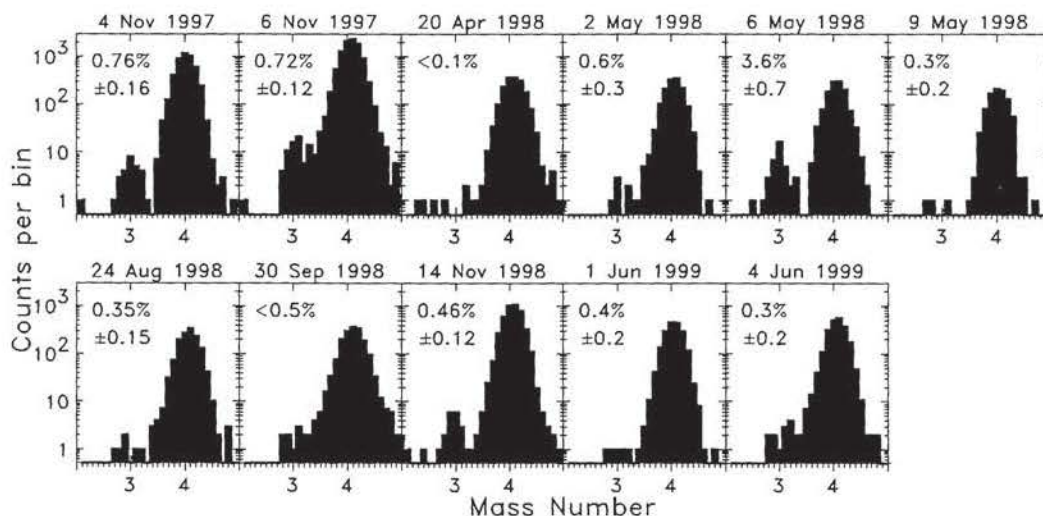


Figure 2. Mass histograms of 7.3–9.7 MeV/nucleon He nuclei from SIS during the 11 SEP events. The $^3\text{He}/^4\text{He}$ ratio (in percent) obtained after applying corrections to equal energy intervals for the two isotopes is indicated for each SEP event.

associated X-ray flares were observed for most of these events (von Rosenvinge et al. 1999; Mason, Mazur, & Dwyer 1999).

Although most of these events appear to be gradual, most also have at least some characteristics which have come to be more commonly associated with impulsive events (Reames 1995a). Many of these events are iron-rich, and the four most iron-rich have elemental abundances and inferred ionic charge states closely matching those of typical impulsive events (Cohen et al. 1999). None of these events has a $^3\text{He}/^4\text{He}$ ratio exceeding 0.1 (“ ^3He -rich”), which had commonly been used to indicate impulsive events (Reames, Meyer, & von Rosenvinge 1994). However, as pointed out by Cohen et al. (1999), most have $^3\text{He}/^4\text{He}$ ratios far in excess of the solar wind value of $\sim 4 \times 10^{-4}$ (Gloeckler & Geiss 1998), as illustrated in Figure 2 and as also seen at lower energies (Mason et al. 1999). Recently, Mason et al. (1999) have proposed that ^3He accelerated by impulsive flares may reside in the interplanetary medium long enough to be available for further acceleration by CME and interplanetary shocks associated with gradual SEP events. Although this mechanism may explain the ^3He enrichment in these large events, preliminary analysis suggests that it cannot by itself fully account for the abundances of other elements that are observed. In any case, one of the outcomes of new ACE measurements appears to be a recognition that from abundance data alone one can not unambiguously distinguish events in which particles were accelerated by coronal or interplanetary shocks from those in which the particles were flare-accelerated (Mewaldt 1999).

Isotopes of elements up through Ni are measured by SIS, as illustrated in Figure 3 by mass histograms of selected species observed in the 14 November 1998 SEP event. Details of the analysis required to obtain isotope abundance ratios from such histograms and listings of the exact time periods used for most events in this study and the energy intervals for each element (typically tens of MeV/nucleon) are given in Leske et al. (1999a,b).

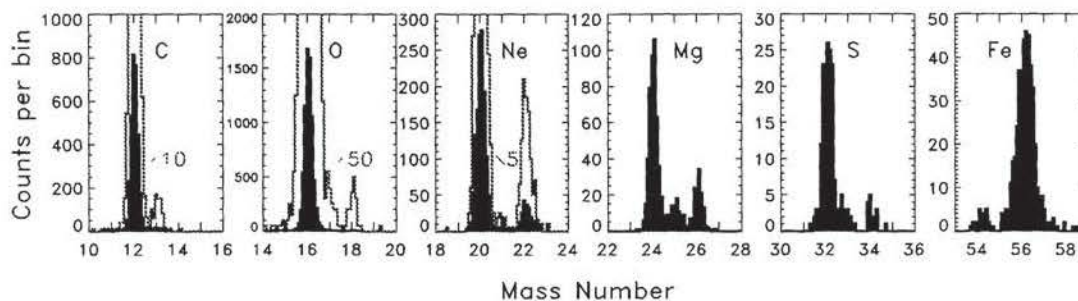


Figure 3. Mass histograms (*shaded*) from SIS, some with expanded scales (*solid lines*), accumulated from 11/14/98 5:00 to 11/16/98 0:00.

3. Results and Discussion

As illustrated in Figure 4, most of the measured isotope abundance ratios are highly variable from event to event, which complicates the use of these data to determine coronal isotopic abundances. Elemental abundance variations of heavy ions in gradual events have been found to scale reasonably well as a power law in Q/M (Breneman & Stone 1985), with a different power law index for each SEP event. If the Q/M ratio is indeed the relevant organizing parameter, the same physical mechanism should produce variations in the isotopic abundances, since Q/M will differ for two isotopes of the same element. Given the abundances of any two elements, e.g., Fe and O, one can calculate the power law index, γ , relating their abundance ratio enhancement to Q/M , provided their ionic charges are known. For two isotopes of an element with the same value of Q but different masses M_1 and M_2 , the expected SEP abundance ratio for M_2 to M_1 is then $(M_1/M_2)^\gamma$ times the corresponding coronal abundance ratio (Mewaldt & Stone 1989). (Note that γ is negative for Fe-rich events.)

The Fe/O ratio is commonly measured in SEPs and used to compare different events. Although reasonably good correlations between isotopic abundances and Fe/O have been shown (Leske et al. 1999b,c), with heavy isotopes found to be preferentially enriched in Fe-rich events, other elemental ratios are more suitable for establishing that elemental and isotopic abundances are governed by the same Q/M -dependent process. The Fe charge state is known to be variable (e.g. Mazur et al. 1999), and it is not usually measured at SIS energies in SEPs, making it very difficult to determine a reliable value for γ . Also, Fe has a low first ionization potential (FIP), while O has a high FIP. The degree of FIP fractionation is known to vary from event to event (Garrard & Stone 1994), which will alter elemental but not isotopic abundances and thus blur the correlation.

For the above reasons, we compare the isotopic abundances in Figure 4 with Na/Mg ratios instead of Fe/O ratios. As pointed out by Cohen et al. (1999), both Na and Mg nuclei are theoretically expected to have 2 electrons attached over a broad range of coronal temperatures (Arnaud & Rothenflug 1985). (Some variability in Q is seen for low energy Mg in SEPs [Möbius et al. 1999], but much less than for Fe.) Also, both Na and Mg have low FIP values, so there should be no significant FIP fractionation between them. The lines in Figure 4 show the expected correlations, assuming only that $Q(\text{Na})=9$, $Q(\text{Mg})=10$, and that the same power law in Q/M required to produce a given Na/Mg ratio also

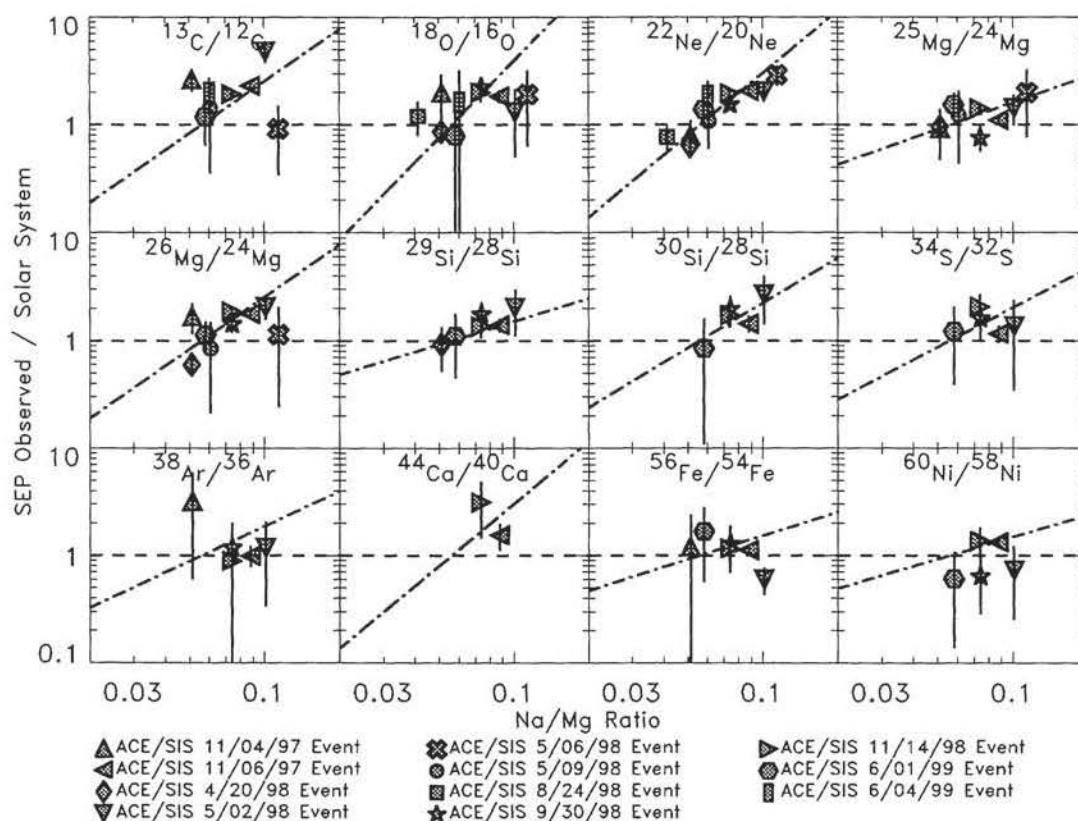


Figure 4. Preliminary values from ACE/SIS of 12 isotope abundance ratios (normalized to solar system values of Anders & Grevesse 1989) plotted vs. the observed Na/Mg ratios in the indicated SEP events. Dashed-dotted lines show the expected correlations for the ratios.

accounts for the isotope enhancement factor. The different slopes of these lines arise simply from the different relative mass number ratios M_1/M_2 , and the data seem to follow these trends. The agreement is best for Ne, which neighbors Na and Mg in both Z and Q/M , but is also fairly good for higher Z , up to about Si. At lower Z , several outliers are seen for ^{13}C and ^{18}O , although most of the points with the smallest uncertainties are near the expected lines.

There may be additional fractionation processes for some of these events which do not scale simply with Q/M . In impulsive events, ion cyclotron wave resonances (Fisk 1978; Temerin & Roth 1992) may selectively enhance the abundances of species with discrete values of Q/M , especially those near a harmonic of the ^3He cyclotron frequency (Bochsler & Kallenbach 1994). If some of these events contain significant contributions from material injected into the interplanetary medium by impulsive events (Mason et al. 1999), this could cause deviations from the simple correlations otherwise expected. For heavier elements, such as S and above, the agreement between the more limited data and the expectations is not as clear. The agreement might break down with increasing distance in Q/M from Na or Mg if the actual dependence on Q/M is not a simple power law as assumed here. By studying additional events SIS should be able to test this hypothesis.

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